

Degenerate Bose-Bose mixture in a three-dimensional optical lattice

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We produce a heteronuclear quantum degenerate mixture of two bosonic species, ^{87}Rb and ^{41}K , in a three-dimensional optical lattice. On raising the lattice barriers, we observe the disappearance of the interference pattern of the heavier ^{87}Rb , shifting toward shallower lattice depths in the presence of a minor fraction of ^{41}K . This effect is sizable and requires only a marginal overlap between the two species. We compare our results with similar findings reported for Fermi-Bose mixtures and discuss the interpretation scenarios proposed to date, arguing that the explanation may be linked to the increased effective mass due to the interspecies interactions.

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Quantum degenerate gases are formidable systems to shine light on fundamental quantum phenomena occurring at extremely low temperatures, such as superconductivity and superfluidity. In combination with optical lattices and scattering resonances, degenerate gases give rise to strongly correlated systems, enriching even further the breadth of phenomena that can be directly probed. Indeed, the pioneering experiment on the superfluid to Mott-insulator transition [1] has shown how physical models long studied in the field of condensed matter can be realized almost ideally. With two different atomic species, the wealth of quantum phases grows to a daunting complexity [2], only marginally explored by experiments. Actually, experiments with heteronuclear mixtures in three-dimensional (3D) optical lattice have been performed very recently only for Fermi-Bose systems [3, 4], while Fermi-Fermi and Bose-Bose mixtures are yet uncharted territory. The importance of mixtures in optical lattices is hardly overstated: association of dipolar molecules [5], mapping of spin arrays [6], schemes for quantum calculation [7], and implementation of disorder [8] represent only a few major research lines that potentially will greatly benefit from such systems. In particular, Bose-Bose mixtures seem well suited for all these purposes, provided that collisional losses are adequately suppressed.

This work reports the first realization of a degenerate Bose-Bose heteronuclear mixture in a 3D optical lattice. Exploiting the large mass difference, we investigate the regime where one species lies well in the superfluid domain, while the other exhibits the disappearance of the interference pattern usually associated with the transition from a superfluid to a Mott insulator. We focus only on the interference pattern and do not probe the shell structure characteristic of a Mott-insulator for trapped systems [9, 10]. We observe that the presence of the superfluid enhances the loss of phase coherence of the second species occurring for increasing lattice strengths.

Surprisingly enough, we find that the effect is sizable (see Fig. 1), not only for small fractions of the minority species, but even for marginal spatial overlap between the two.

The experimental setup has been described earlier [11, 12]. Here we briefly outline the production of a double Bose-Einstein condensate (BEC), first demonstrated in [13]. We capture 2×10^8 ^{87}Rb atoms and a variable number of ^{41}K atoms in the stretched $|F = 2, m_F = 2\rangle$ states in a Ioffe millimetric trap (MMT) [12, 14] and we start evaporation by lowering the MMT depth from 5 to 3.5 mK, with final harmonic frequencies $(\omega_x, \omega_y, \omega_z) = 2\pi \times (16.8, 202, 202)$ Hz [15]. We then cool ^{87}Rb only by microwave evaporation, while ^{41}K is cooled sympathetically. A single sideband, 10 dB below the carrier, selectively removes ^{87}Rb atoms in the $|F = 2, m_F = 1\rangle$ state, which would quickly deplete the ^{41}K sample. BEC is achieved first for ^{41}K at 250 nK and then for ^{87}Rb : condensates contain typically $4(2) \times 10^4$ $^{87}\text{Rb}(^{41}\text{K})$ atoms, with Thomas-Fermi radii of $2.4(2.2) \mu\text{m}$ and peak densi-

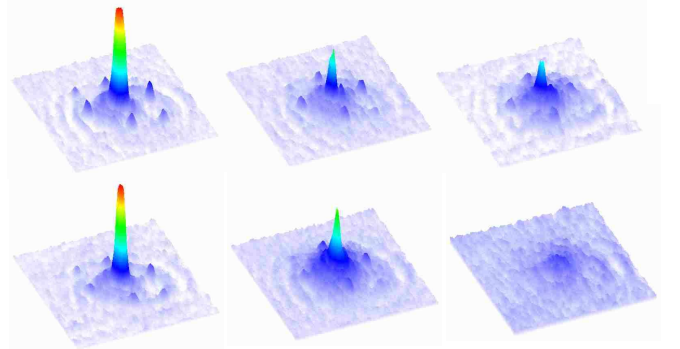


FIG. 1: (Color online): Interference pattern of ^{87}Rb for $s = 6, 11, 16$ (left to right). Upper row: ^{87}Rb only; lower row: ^{87}Rb mixed with ^{41}K (not shown). Each panel represents the column density over an area $175 \mu\text{m} \times 135 \mu\text{m}$.

ties of $1.4(0.9) \times 10^{14} \text{ cm}^{-3}$.

In the presence of 2×10^3 ^{41}K atoms clearly condensed (inverted ellipticity after expansion), since no thermal cloud can be detected, our sensitivity places an upper bound of 50% on the thermal fraction of this species: this sets an upper bound on the temperature of 73 nK. Since the evaporation is stopped at the same level also in the absence of ^{41}K , the same temperature boundary applies also for ^{87}Rb alone. At 73 nK, the peak density of the ^{41}K thermal atoms is lower than 1/60 that of the condensate. For this reason, we will throughout neglect the ^{41}K thermal fraction in the following.

The clouds are only partially overlapped: due to differential gravity sag, the ^{87}Rb condensate lies $3.2 \mu\text{m}$ below ^{41}K . Also, numerical integration of the 3D Gross-Pitaevskii equation (GPE) shows that both density distributions are deformed and almost completely phase separated, due to the strong K-Rb repulsion [16]. Indeed, the interspecies scattering length $a_{K-Rb} = 163a_0$ [17] is much larger than both $a_{Rb} = 99a_0$ [18] and $a_K = 65a_0$ [19], with a_0 the Bohr radius.

Once double BEC is achieved, we ramp three retro-reflected optical lattice beams at $\lambda_L = 1064 \text{ nm}$, with frequencies differing by tens of megahertz, propagating along the x, y , and z axes and focusing at the center of the MMT with waists equal to $(90, 180, 160) \mu\text{m}$. The lattice strength is calibrated by means of Bragg oscillations and Raman-Nath diffraction [20], yielding a systematic uncertainty of 10%, which must be added to the statistic uncertainties quoted hereafter. We choose the duration and time constant of the exponential turn-on profile, 50 and 20 ms, respectively, by maximizing the visibility of the ^{87}Rb interference pattern. We wait for 5 ms with the optical lattice at full power and abruptly switch off the lattice beams ($< 1 \mu\text{s}$) and the MMT current ($\sim 100 \mu\text{s}$). We image both species after a typical time of flight of 15 to 20 ms with resonant absorption: the interference peaks of ^{87}Rb are progressively smeared as the lattice strength is ramped at higher values.

We measure the width of the central peak and the visibility v of the interference pattern, defined as [22] $v = (N_p - N_d)/(N_p + N_d)$, where N_p and N_d denote, respectively, the summed weights of the first lateral peaks and of equivalent regions at the same distance from the central peak along the diagonals [see Fig. 2(e)]. At our lattice wavelength, the optical potential is the same within 10% for ^{87}Rb and ^{41}K . However, due to their larger mass and scattering length, ^{87}Rb atoms tunnel less and repel each other more: the combined effect is that ^{87}Rb loses phase coherence at lower lattice power than ^{41}K .

The main experimental result of this work is the observation that the lattice strength at which the ^{87}Rb interference pattern starts washing out is greatly shifted not only by a minor admixture of ^{41}K atoms, but also with a marginal spatial overlap. These findings, displayed in

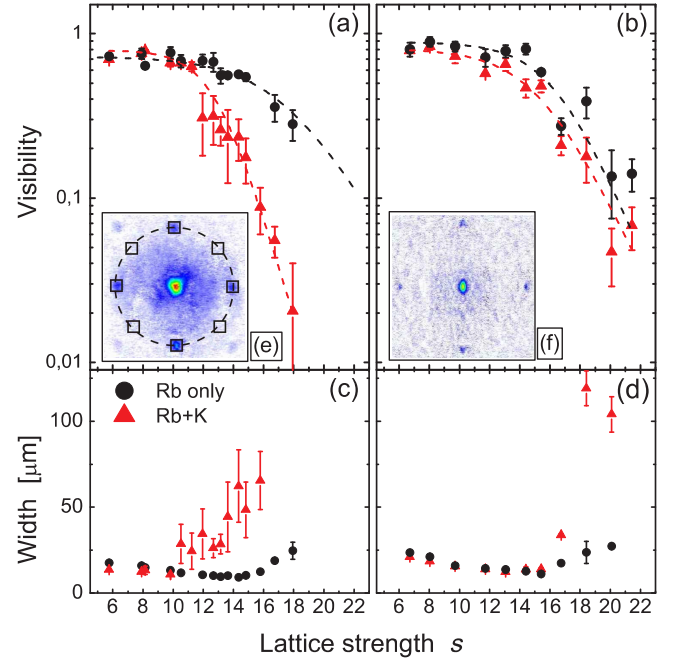


FIG. 2: (Color online) Visibility and width of the central peak of the ^{87}Rb interference pattern, for partial (a,c) and zero (b,d) overlap with the ^{41}K condensate. In each panel we compare data and fit (dashed lines) with ^{41}K atoms (red) and without (black), i.e. with $N_K = 2(1) \times 10^3$ and 0. The insets show: how visibility of ^{87}Rb is extracted from images (e) and the interference pattern of ^{41}K visible for $s=20$ (f).

Fig. 1, augment those of similar experiments carried out with the mutually attractive ^{40}K - ^{87}Rb Fermi-Bose mixture [3, 4].

To quantify the shift of the transition point, we plot the visibility and the width of the central peak versus the lattice strength in units of the ^{87}Rb recoil energy s [21]. We compare data taken with ^{41}K and when ^{41}K was not even loaded in the MMT (Fig. 2). We fit the visibility with a phenomenological Fermi function $v = v_0/[1+\exp(\alpha(s-s_c))]$, which has the expected flat behavior below the critical lattice strength s_c and decreases exponentially for $s \gg s_c$. From the fit, we find that, for $N_{Rb} = 3 \times 10^4$, the critical s value is $s_c = 16.8 \pm 0.4$ for ^{87}Rb only, while $s_c = 12.4 \pm 0.3$ with $N_K = (2 \pm 1) \times 10^3$.

Using the formula $\eta = 0.696s^{-0.1} \exp(2.07\sqrt{s})(a/\lambda_L)$ [22], we relate s with the ratio of interaction to tunneling matrix elements, $\eta = U/(6J)$, in terms of the lattice wavelength λ_L and the scattering length a . From the fit values, we derive both the critical value η_c and the exponents of the visibility decay for $s \gg s_c$, $v \sim \eta^{-\nu}$: without ^{41}K we find $\eta_c = 12.3^{+6.2}_{-4.3}$ and $\nu = 2.3^{+0.6}_{-0.4}$, but with ^{41}K we have $\eta_c = 3.9^{+1.6}_{-1.2}$ and $\nu = 3.4^{+0.8}_{-0.5}$ (error bars are dominated by the calibration uncertainty of the lattice strength).

The width of the central peak measures the inverse

correlation length: it signals the transition with a stark climb at $s \simeq 10$ in the presence of ^{41}K and $s \simeq 14$ in the absence thereof [see Figs. 2(c) and 2(d)]. After the transition, the width increase is steeper in the presence of ^{41}K even for null overlap (Fig. 2(d)): this behavior is unexpected and so far unexplained. While the transition points detected by the width and the visibility are different, the shift is the same, $\Delta s_c \simeq 4$.

Such a shift is surprising, given the little overlap between the two species. Numerical integration of the 3D GPE with an $s = 11$ vertical lattice shows that the overlap is restricted to one lattice site out of 11 (see Fig. 3). Generalizing to a 3D lattice, we expect that approximately only 10% of sites are simultaneously filled with both ^{87}Rb and ^{41}K atoms. In order to check that the shift is genuinely related to the interspecies interaction, we repeat the experiment with larger differential sag of the two samples. Once the double-species BEC is achieved, we relax the MMT harmonic frequencies to $\bar{\omega} = 2\pi \times (9.2, 108, 108)$ Hz, thereby increasing the vertical separation to $11\text{ }\mu\text{m}$, so that the overlap is totally negligible even for any undetected ^{41}K thermal cloud ($1/e^2$ radius = $7.7\text{ }\mu\text{m}$). Figures 2(b) and 2(d) show that, although the visibility is slightly lower in the presence of ^{41}K , the transition point is the same within our error bars: $s_c = 15.8(0.5)$.

As a further test, we investigate the effect of the lattice turn-on ramps. As mentioned, for ^{87}Rb alone, the visibility is maximum for a ramp of 50 ms. *A priori*, this ramp duration could be insufficient in the presence of ^{41}K impurities. Therefore, we monitor the visibility versus the ramp duration. The turn-on profile follows essentially an exponential function with a time constant equal to 0.4 of the total ramp duration, smoothed at the end. We find that the visibility decreases for turn-on times longer than

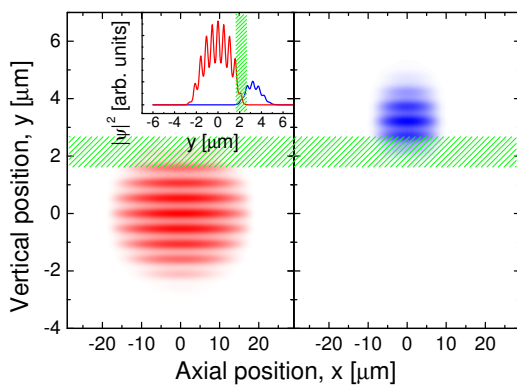


FIG. 3: (Color online): density distribution of ^{87}Rb (red, left) and ^{41}K (blue, right) atoms, in the plane $z = 0$, calculated by numerical integration of the GPE: $N_{\text{Rb}} = 3 \times 10^4$, $N_{\text{K}} = 2 \times 10^3$, vertical lattice strength $s = 11$. Shaded area (green) highlights the overlap, while the inset plot reports density profiles along the vertical line through $x = 0$.

50 ms also in the presence of ^{41}K (see Fig. 4) and indeed the visibility difference is roughly constant at 15%. We conclude that, while in principle one could expect that in the presence of ^{41}K the lattice ramp should be slower, there is no evidence that this is indeed the case, at least as far as the loss of visibility is concerned. Moreover, we do not observe a significant change in the number of atoms with the duration of the ramp; hence three-body losses play a negligible role, consistently with the small overlap of the two clouds.

As mentioned, our experimental findings extend those of Refs. [3, 4] to *bosonic* impurities and help to shine some light on the induced loss of coherence, whose origin has so far remained unclear, if not controversial. Günter *et al.* report that the transition point, extracted from the visibility data with a fitting procedure equivalent to ours and expressed in terms of η_c , shifts from 6.5 to 2.5 for an 8% admixture. Both values are lower than ours. Ospelkaus *et al.* instead quantify the shift in terms of s_c , as we do, and fit the visibility with the Fermi function. The reported shift $\Delta s_c = 3(1.5)$ for a 7 % fraction of impurities agrees with our result. With the same data, but measured from the width of the central peak, the transition point shifts from $\eta_c = 9$ to 4.5 [3] and by $\Delta s_c = 1(1)$ [4].

Several different scenarios have been proposed to explain the impurities-induced loss of coherence. We discuss here the impact of our experiment on these scenarios.

First, we notice that one would naively expect that strongly interacting impurities would locally increase the ^{87}Rb atom filling factor and hence the chemical potential, by expelling or attracting them. However, increasing the chemical potential leads to an enhancement of the superfluid fraction, which is indeed the result predicted by Ref. [5], but opposite to what we observe. Ospelkaus *et al.* argue that fermionic atoms act like randomly localized scatterers for the boson order parameter, thereby splitting it into isolated superfluid domains unable to maintain a single coherent phase throughout the sample [4]. The suggested phenomenon, reminiscent of Anderson localization, depends crucially on the fermionic nature of the ^{40}K impurities, leading to localization. However, bosonic ^{41}K atoms are expected to localize less, not more, than ^{87}Rb . Therefore, the interpretation based on Andersonlike localization does not hold in our case and might be unnecessary for the Fermi-Bose experiments.

The loss of phase coherence could follow from heating of the two clouds when the lattice ramps up. In addition to technical noise, which plays a role only at longer time scales, we consider the effect of the thermodynamic transformation involved. With two species, the effective masses change at different rates and thermal equilibrium requires an interspecies redistribution of entropy. In our experiment, this increases the entropy of ^{87}Rb and therefore its thermal component. Quantitatively, due to the small overlap, we neglect the interspecies interaction en-

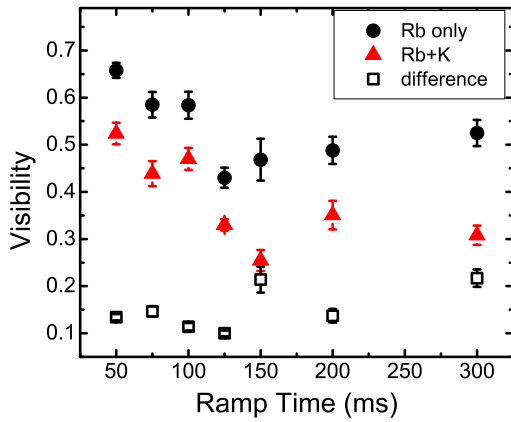


FIG. 4: (Color online) Visibility of the fringes at $s = 12$ versus the duration of the lattice ramp up.

ergy and calculate the total entropy as the sum of two independent contributions. At $s = 0$, we calculate the contribution of each component from the formula for the total energy: $E/N = 3k_B T_c \zeta(4)t^4/\zeta(3) + \mu(1-t^3)^{2/5}(5+16t^3)/7$, with $t = T/T_c$, where T_c and μ denote the critical temperature and the chemical potential [23]. At $s = 20$ the contribution of ^{41}K is given by the above formula (replacing the atomic mass with the effective mass of the lowest energy band), while for the contribution of ^{87}Rb we take that of a deep Mott insulator [24]: $S_{\text{shell}}/k_B = 32\pi^3 k_B T \sum_j R_j/(3m\omega^2 \lambda_L^3)$, where R_j and m indicate the radii of the superfluid layers of the Mott shell structure and the atomic mass. For an initial temperature of 73 nK (^{87}Rb thermal fraction equal to 0.21), the presence of ^{41}K increases the ^{87}Rb entropy and hence its thermal fraction, by 20%. As a consequence, the ^{87}Rb condensate fraction decreases from 79% to 75% and the visibility by approximately the same amount [25]. We conclude that this is a minor effect.

A plausible interpretation of our findings invokes the dressing of ^{87}Rb atoms by ^{41}K : naively, dressed ^{87}Rb atoms weigh more, therefore tunnel less. This argument is made quantitative by Bruderer *et al.* [26], who analyze the generation of polarons in a Bose-Bose mixture, i.e., quasiparticles composed of localized atoms (^{87}Rb) plus a cloud of superfluid phonons of the other species (^{41}K). The polarons have two different effects: at zero temperature they reduce the tunneling rate of ^{87}Rb atoms according to the picture outlined above; at finite temperature, ^{41}K phonons undergo incoherent scattering, further hampering the hopping of ^{87}Rb . According to Ref. [26], with the parameters of our experiment at $s = 10$, the energy scale relevant for the onset of the incoherent scattering is $E_p/k_B \approx 1$ nK and therefore it is comparable to and lower than the estimated lattice temperature, ranging from 10 to 30 nK, while the tunneling suppression at $T = 0$ appears negligible. The analysis carried out in

Ref. [26] relies on suitably weak interspecies interactions. In our experiment the effective interspecies interactions are reduced by the low density of ^{41}K in the overlap region but the approximations of Ref. [26] are only weakly satisfied. The order of magnitude of the above value, however, proves that the inhibition of tunneling due to incoherent scattering of phonons deserves a deeper analysis.

Finally, we address the question of why the shift is substantial even with the small overlap shown by Fig. 3. We conjecture that, owing to the inhomogeneous density, the loss of coherence starts from the borders of the ^{87}Rb condensate where the filling factor is lower; the overlap with ^{41}K , although small, occurs in this critical region. Alternatively, one could call on collisions occurring during the expansion: since we do not observe any degradation of the ^{87}Rb Raman-Nath diffraction pattern caused by the presence of ^{41}K , time-of-flight collisions between the two species seem unable to significantly alter the ^{87}Rb momentum distribution, at least in the superfluid regime.

In summary, we have created a degenerate Bose-Bose mixture in a 3D optical lattice and studied the influence of a minor admixture of superfluid ^{41}K on the loss of ^{87}Rb phase coherence. We find that this loss is furthered in the presence of ^{41}K , even if the two clouds overlap only at their boundaries. Our results agree qualitatively with similar observations carried out with a Fermi-Bose mixture, notwithstanding the different statistics of impurities and the opposite sign of the strong interspecies interactions. Following a recent theoretical analysis, we find that the activation energy of polarons is of the same order as the estimated temperature in our optical lattice. Our degenerate Bose-Bose mixture will also be studied in the double Mott-insulator regime, promising for the formation of stable molecules. To this end, Feshbach resonances predicted at moderate magnetic fields are instrumental to control the interspecies interactions.

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